

Regular Article

Effects of temperature and humidity on the contact angle of pesticide droplets on rice leaf surfaces

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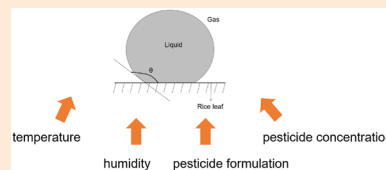
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The effects of external factors such as temperature, humidity, pesticide formulation, and pesticide concentration on the contact angle of pesticide droplets on rice leaf surfaces were analyzed. The experiments showed that there were significant differences in the contact angles of droplets on the leaf surfaces under different temperatures and humidity. As the ambient temperature increased, the contact angle first decreased and then increased, reaching a minimum value at 25°C. With a gradual increase in humidity, the contact angle significantly increased and reached a maximum at 100% humidity. Finally, it was concluded that both the formulation and concentration of the pesticide had a significant effect on the contact angle of droplets on rice leaf surfaces. The experiments also illustrated that the effects of the pesticide formulation and concentration on the contact angle were more significant than those of temperature and humidity.



Keywords: contact angle, rice leaf surfaces, temperature, humidity, pesticide formulation, pesticide concentration.

Introduction

Rice is an important grain planted in large areas in China.¹⁾ Recently, rice diseases, insects, and weeds have been increasing annually. Currently, chemical control is the main prevention and control method.²⁾ Pesticides play an extremely important role in agricultural production.³⁾ Although pesticide use can increase crop yields in the short term, their excessive use leaves many hidden dangers that can be easy to ignore. For example, pesticide droplets can easily roll off the surface of rice leaves,^{4,5)} causing only 20–30% of the pesticides to be deposited on the target. The remaining 70–80% is lost to the soil,⁶⁾ which leads to the pesticide having a low degree of wet spreading on the plant foliage^{7,8)} and causing ecological pollution.^{9–12)} Therefore, one of the key challenges regarding current pesticide application tech-

nology is to improve the utilization rate of pesticides, which can be accomplished by studying the wet-distribution effect of liquid pesticides on the surface of rice leaves.^{13,14)}

The leaf surface is a barrier that separates plant tissues from the environment.¹⁵⁾ It plays an important role in protecting the internal structure of the leaf, and it resists the influence of different external environments.^{16,17)} Spray droplets can attach to the leaf surface to improve the utilization of pesticides. The contact angle on the surface of the plant leaves is an important indicator that can be used to measure the wetting properties of a liquid.^{18–20)}

The phenomenon of liquid diffusion on the surface of isotropic plant leaves is called wetting.^{21,22)} The ability of a liquid to diffuse on a solid surface is called the wettability of the liquid to the solid.^{23,24)} Wetting spread is a phenomenon in which one fluid replaces another fluid on the interface, usually referring to the process by which a liquid replaces a gas on a solid surface. The wetting and distribution of a liquid on the surface of rice leaves, which is generally represented by the contact angle,^{25,26)} reflects the affinity of the rice leaf surface for pesticide droplets. The contact angle of droplets on rice leaves is affected by internal and external factors. Internal factors mainly include the rice variety, the chemical fractionation of wax deposited on the leaf surface,²⁷⁾ physical microstructures,²⁸⁾ leaf position, and the plant growth

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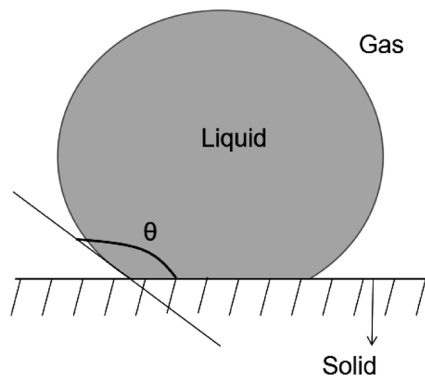


Fig. 1. Contact angle schematic.

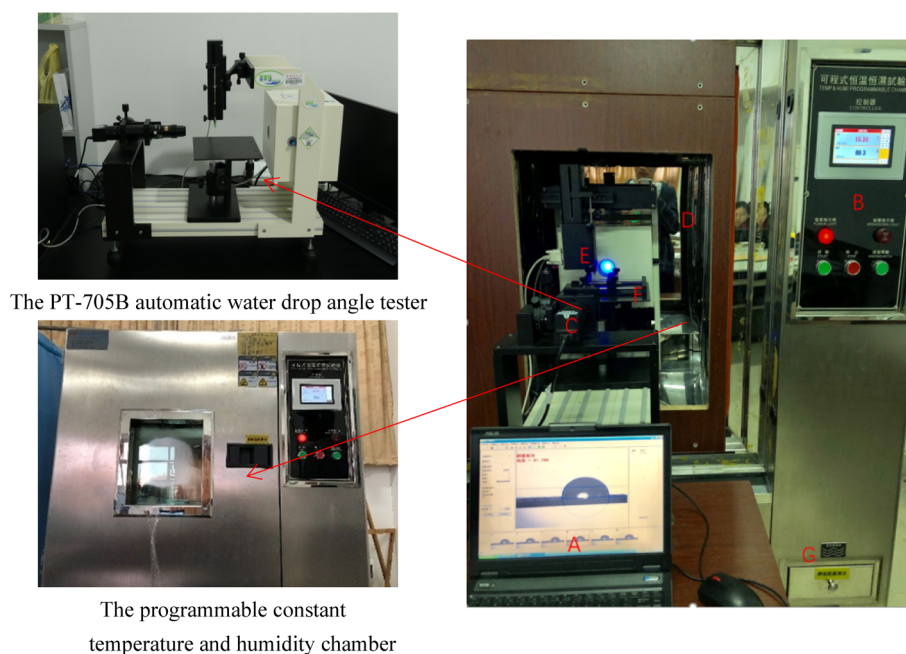
cycle. External factors affect the contact angle by changing the environmental conditions around the leaf surface and the properties of the liquid, including the type and concentration of surfactants, the type and concentration of organic solvents, the solution viscosity, droplet volume, temperature, and humidity.

Contact angle is the most direct indicator of wetting and spreading properties. For most plants, the wetting and spreading performance on plant leaves can be analyzed by measuring the contact angle between droplets and the leaf surface. Contact angles less than 90° indicate wetting, and the droplets can adhere to the solid surface or even spread. Contact angles greater than 90° indicate non-wetting. If the contact angle is much larger than 90° , the droplets will aggregate into water droplets and roll off.²⁹⁾ The contact angle is shown in Fig. 1.

During plant growth, the temperature and relative humidity of the environment are critical external factors.^{30,31)} These two

environmental factors greatly affect the physical and chemical properties of leaf surfaces, thus affecting the contact angle of droplets on the surface of rice leaves. Therefore, many researchers have recently explored the effects of temperature³²⁾ and humidity³³⁾ on the droplet contact angle. Baker³⁴⁾ explored the effects of temperature and relative humidity on the wettability of cabbage leaf surfaces and concluded that a decrease in temperature or relative humidity would reduce the wettability. In a study on rice and lotus leaves, Sun³⁵⁾ also mentioned the important influence of temperature on leaf surface wetting diffusion. The results of the study showed that the contact angle of droplets on the surfaces of experimental plant leaves remained constant within a certain temperature range. After reaching a certain temperature, the contact angle began to linearly decline. When the experimental temperature reached 56°C , the contact angle of the droplets on the surface of the lotus and rice leaves was approximately 120° . At this temperature, the rice leaf contact angle decreased at the highest rate. As the ambient temperature continued to rise, the contact angle of the droplets on the surfaces of the lotus and rice leaves decreased, and it was minimized when the ambient temperature reached 69°C . In the ambient temperature range of $56\text{--}69^\circ\text{C}$, the contact angle of the droplets on the surfaces of the lotus and rice leaves changed significantly.

In this study, the effects of four main external factors, namely ambient temperature, relative humidity, pesticide formulation, and pesticide concentration, on the contact angle of droplets on rice leaves during a simulated agricultural aviation rice-field spraying operation were investigated using an automatic contact-angle tester. The impacts of these four factors were then obtained. This study considered the temperature and humidity



The PT-705B automatic water drop angle tester

The programmable constant temperature and humidity chamber

Fig. 2. The experimental environment was designed and constructed to measure the contact angle of droplets on the surface of rice leaves under different temperature and humidity conditions. (A) Measuring computer; (B) numerical control board for the incubator; (C) high-speed camera; (D) internal environment of the test chamber with constant temperature and humidity; (E) drop injector; (F) fixed experimental platform; (G) water tank.

Table 1. Experimental factors and levels

Experimental factors	Levels						
Temperature	15°C	20°C	25°C	30°C	35°C	40°C	45°C
Humidity	40%	50%	60%	70%	80%	90%	100%
Pesticide formulation	EC	SC	WP	WG	SL		
Pesticide concentration	1:100	1:200	1:500	1:1000	1:2000	1:3000	1:4000

ranges of rice plants in the general planting environment to be the independent variables and the rice leaf contact angle to be the dependent variable. Finally, this study explored the interaction effect of ambient temperature and relative humidity on the leaf contact angle of rice plants.

Materials and methods

1. Materials

Three rice varieties (Guang 8 You 169, He Mei Zhan, and Mei Xiang Zhan 2) were selected from the agriculturally dominant rice varieties released by the Guangdong Provincial Department of Agriculture. These varieties are widely used in Guangdong and the rice-planting regions of southern China, and they have good prospects for popularization and application.

To avoid any effects of other variables on the experiment, the test rice materials were uniformly planted in a rice test field at the South China Agricultural University. The penultimate leaves in the middle of the rice plants were selected as the experimental samples. In order to keep the rice leaves fresh, they were packed and sealed in polyethylene bags and transported to the laboratory immediately after each field-sampling session. The bottoms of the rice leaves were immediately placed in a container of distilled water to prevent the leaves from curling up, which would have prevented the contact angle of the droplets on the leaf surfaces from being measured. Before the experiment, the rice leaves were cut into 8 cm-long rectangles. The samples were then adhered to glass slides with double-sided tape, and the edges were lightly compacted to prevent curling. Finally, the slides were placed on a platform for measurement. During the measurements, external objects were prevented from contacting the rice leaf surfaces to avoid damaging the leaf surface structures.

2. Experimental instruments and tools

A PT-705B automatic water-drop angle tester (Dong Guan Precise Test Equipment Co., Ltd., China) and a programmable constant temperature and humidity tester (Shang Hai Jiang Kai Machine Co., Ltd., China) were used in the experiment, as shown in Fig. 2. The automatic water-drop angle tester was equipped with

a precise automatic liquid-distribution system. The programmable constant temperature and humidity tester had a temperature accuracy of 0.1°C and a humidity accuracy of 0.1%.

3. Methods

The external factors considered in this study were categorized as environmental or chemical factors. The environmental factors were temperature and relative humidity. The chemical factors were pesticide formulation and pesticide concentration.

The experimental platform that was built for this study is shown in Fig. 2. The contact angle was measured using an automatic water-drop angle tester. The experiment was carried out in a chamber with programmable constant temperature and humidity, and the temperature and humidity were adjusted according to the experimental requirements. A high-speed camera equipped with the drop angle tester was used to capture the droplet, and the shape of the droplet was collected using an optical amplification system and an image acquisition system. Finally, the contact angles of droplets on the rice leaf surfaces were measured using the ellipse fitting method^[36] with the automatic water-drop angle tester.

3.1. Experiment on the influence of single factors on the contact angle of rice leaves

First, the effects of temperature and humidity on the surface contact angle of rice leaves were explored. The three rice varieties (Guang 8 You 169, He Mei Zhan, and Mei Xiang Zhan 2) were arranged for measurement of the contact angle at different temperatures and humidity levels using a uniform pesticide formulation with a dilution ratio of 1:200 as the suspension agent. The experimental factors and levels are shown in Table 1. The temperature levels were 15°C, 20°C, 25°C, 30°C, 35°C, 40°C, and 45°C, and the humidity levels were 40%, 50%, 60%, 70%, 80%, 90%, and 100%. Then the effects of the pesticide formulation and concentration on the rice leaf surface contact angle were studied. The experiment to measure the contact angle on rice variety Guang 8 You 169 was designed under unified conditions of 30°C, 70% humidity, and different pesticide formulations and concentrations. Five widely used pesticide formulations were

Table 2. Experimental factors and levels

Experimental factors	Levels				
Temperature	20°C	25°C	30°C	35°C	40°C
Relative humidity	40%	60%	80%	100%	
Pesticide formulation	EC	SC	WP	WG	SL
Pesticide concentration	1:100	1:200	1:500	1:1000	

utilized in this experiment: a 5% imidacloprid emulsion (5% imidacloprid EC), a 35% imidacloprid suspension (35% imidacloprid SC), a 10% imidacloprid wettable powder (10% imidacloprid WP), a 70% imidacloprid water dispersible granule (70% imidacloprid WG), and a 10% imidacloprid soluble concentrate (10% imidacloprid SL). They were produced by Xinyi Nong Plant Protection, Jiaduo Collects Genuine Agricultural Materials, Fengge China Agricultural Materials, MinYuan Agricultural Materials, and Green Field Plant Protection, respectively. Different concentrations of pesticides were distinguished by the dilution ratio of the pesticide stock solution, which was obtained by adding deionized water to an imidacloprid pesticide stock solution. The specific dilution ratios were 1:100, 1:200, 1:500, 1:1000, 1:2000, 1:3000, and 1:4000.

3.2. Effect of temperature and humidity interaction on rice leaf contact angle

The leaf contact angles of the three rice varieties under different combinations of temperature and humidity were determined under the condition that the pesticide formulation was a suspension agent and the pesticide concentration was 1:200. The ambient temperature levels were 20°C, 25°C, 30°C, and 35°C, and the ambient relative humidity levels were 40%, 50%, 60%, 70%, 80%, 90%, and 100%. Contact angle measurement experiments with different combinations of temperature and humidity were conducted, and each experiment was repeated 12 times. The maximum and minimum values were removed, and the average value of the remaining 10 contact angles was taken as the final experimental result. Finally, IBM SPSS Statistics Software (SPSS Inc., USA) and Design-Expert software (Stat-Ease, USA) were used to analyze the influence of temperature and humidity on the contact angle of droplets on the rice leaf surface.

3.3. Multilevel mixed orthogonal experiment

To explore the influence of the four external factors (temperature, relative humidity, pesticide formulation, and pesticide concentration) on the contact angle of the rice leaf surfaces, 25 groups of mixed orthogonal experiments were designed according to the experimental factors and levels in Table 2. The measurements were repeated 12 times for each group, and the maximum and minimum values were removed. The average value of the remaining 10 contact angles was taken as the final experimental result. SPSS software was used to analyze the experimental data using a multifactor analysis of the general linear model. Finally, the degree of influence of each factor was recorded, and the degree of influence of each external factor was obtained through analysis with Design-Expert software.

Results

1. Univariate analysis

1.1. Effect of temperature on the contact angle of droplets on rice leaf surfaces

The experimental results showed that the measured contact angles on the leaf surfaces of the three rice varieties varied with the ambient temperature, as shown in Fig. 3. At different ambient temperatures, the contact angles of the droplets on the surfaces

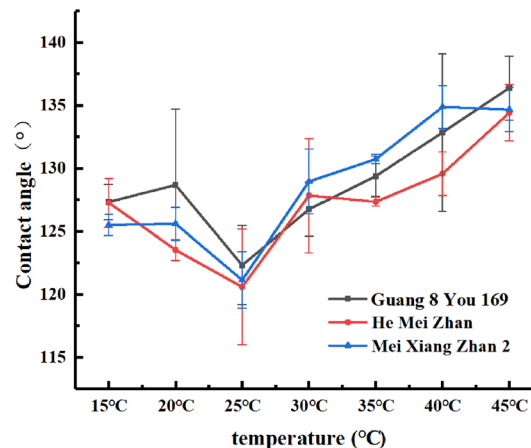


Fig. 3. Relationships between the leaf contact angles of three rice cultivars and temperature.

of the rice leaves were significantly different. With an increase in ambient temperature from 15 to 45°C, the leaf contact angles of the three rice varieties changed significantly. The leaf contact angles of the three tested varieties ranged from 120 to 135°. The contact angle of Guang 8 You 169 increased from 127.331 to 136.384°, which was an increase of 7.1%; that of He Mei Zhan increased from 127.279 to 134.327°, an increase of 5.6%; and that of Mei Xiang Zhan 2 rose from 125.503 to 134.676°, an increase of 7.3%. In the ambient temperature range of 15–25°C, the rice leaf contact angle decreased significantly and reached its minimum at approximately 25°C. When the ambient temperature continued to rise from 25 to 45°C, the contact angle tended to increase, and the wetting and spreading effects became weaker. Therefore, in the rice-planting environment, when the external temperature was approximately 25°C, the contact angle was the smallest, and the droplets had the best wettable spreading effects on the surface of rice leaves.

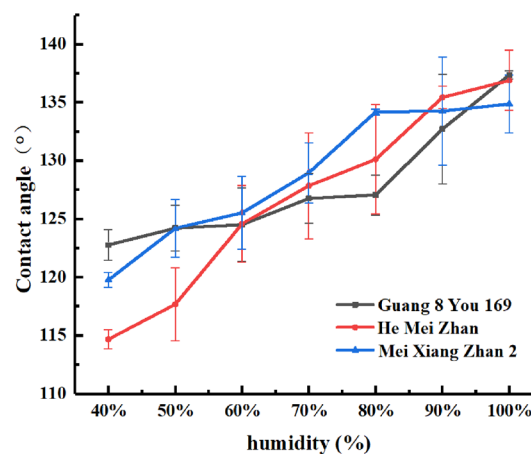


Fig. 4. Relationships between the leaf contact angles of three rice cultivars and relative humidity.

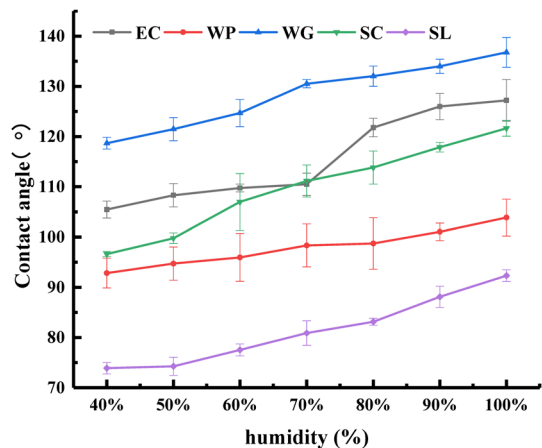


Fig. 5. Relationships between the leaf contact angle of rice and relative humidity under different formulations of imidacloprid.

1.2. Effect of humidity on the contact angle of droplets on rice leaf surfaces

The change in the leaf contact angle of the three rice varieties with humidity was measured experimentally. As shown in Fig. 4, the leaf contact angles of the three rice varieties exhibited obvious changes with an increase in environmental humidity from 40 to 100%. The leaf contact angles of the three rice varieties were all in the range of 115.0–137.5°. The contact angle of Guang 8 You 169 increased from 122.766 to 137.361°, which was an increase of 11.9%. The contact angle of He Mei Zhan increased from 114.67 to 136.901°, an increase of 19.4%. The contact angle of Mei Xiang Zhan 2 increased from 119.758 to 134.867°, an increase of 12.6%. In the range of 40–100% relative humidity, the rice leaf contact angle increased with the gradual increase in environmental relative humidity. The contact angle reached its maximum when the relative humidity was 100%, when the wetting and spreading effects of the liquid on the rice leaf surface were the worst. The contact angle reached its minimum when the relative humidity was 40%, when the wetting

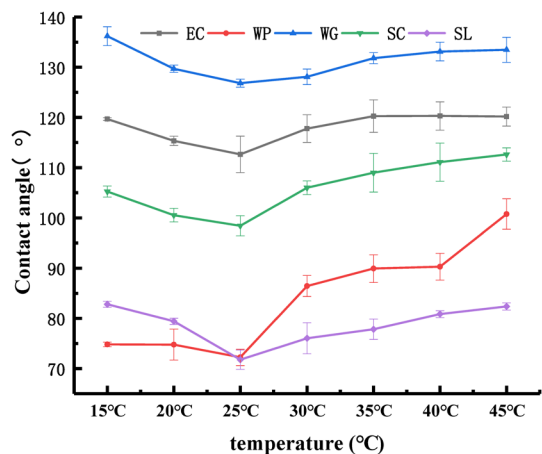


Fig. 6. Relationships between the leaf contact angle of rice and temperature under different formulations of imidacloprid.

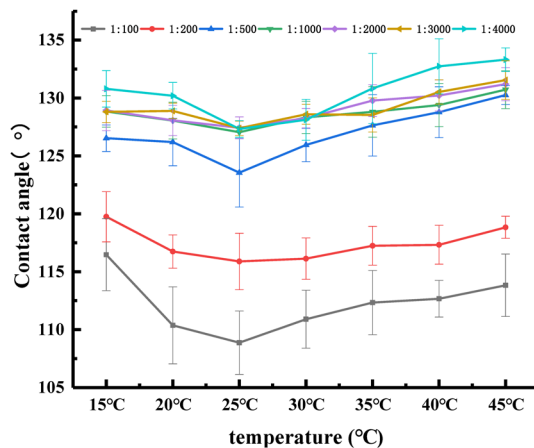


Fig. 7. Relationships between the leaf contact angle and temperature under different concentrations of imidacloprid.

and spreading effects of the liquid on the rice leaf surface were the best.

1.3. Effect of pesticide formulation on the contact angle of rice leaf surfaces

For five different formulations of the pesticide imidacloprid, the droplet contact angle on the rice leaf surface varied with ambient temperature and relative humidity, as shown in Fig. 5 and Fig. 6. It can be concluded from the figures that the variable trends in the contact angles with the five pesticide formulations on the rice leaf surface under different temperatures and humidity are consistent with the results presented in Sections 3.1.1 and 3.1.2. Finally, the values of the contact angles for the five pesticide formulations were ranked as follows: WG>EC>SC>WP>SL. Therefore, the differences in the numerical values of the droplet contact angles for the five pesticide formulations suggest that the effects of different formulations of the same pesticide on the rice leaf contact angle are significantly different.

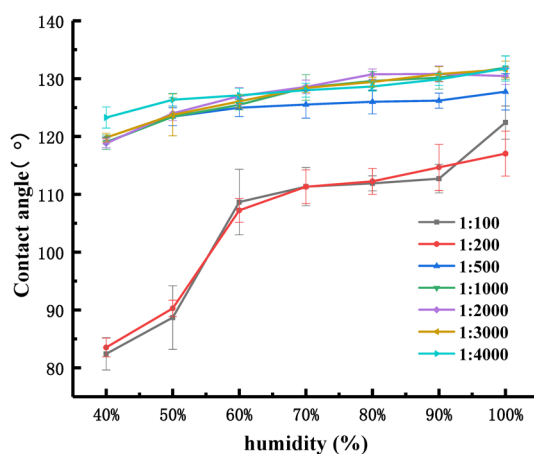


Fig. 8. Relationships between the leaf contact angle and humidity under different concentrations of imidacloprid.

Table 3. Tests of Between-Subject Effects

Source	Type III Sum of Squares	df	Mean Square	F	<i>p</i> -value
Corrected Model	674.236 ^{a)}	26	25.932	7.643	0.280
Intercept	381792.777	1	381792.777	112523.245	0.002
Temperature*humidity	15.954	17	0.938	0.277	0.926
Temperature	98.100	3	32.700	9.637	0.231
Humidity	551.179	6	91.863	27.074	0.146
Error	3.393	1	3.393		
Total	390200.428	28			
Corrected Total	677.629	27			

^{a)} R-Squared=0.995 (Adjusted R-Squared=0.865)

1.4. Effect of pesticide concentration on the droplet contact angle on rice leaf surfaces

Figure 7 shows the change in the contact angle of seven different concentrations of imidacloprid on the surface of rice leaves at different environmental temperatures. As shown in the figure, the trends of the contact angles of the seven pesticide concentrations on rice leaf surfaces with changing temperature were consistent with the results presented in Section 3.1.1. Overall, the contact angles of the droplets on the rice leaf surfaces were significantly different for different pesticide concentrations, and they were roughly divided into three categories. In the first category, the contact angles of pesticides with the highest dilutions (1:1000, 1:2000, 1:3000, and 1:4000) were the largest, similar to the contact angle of water on the rice leaf surface. In the second category, the contact angle of the moderately diluted solution (1:500) decreased by approximately 2.5–3° compared with those in the first category. In the third category, the contact angles of the pesticides with the lowest dilutions (1:100 and 1:200) were significantly lower, with the lowest contact angle being approximately 107° at 25°C.

Figure 8 shows the curves of the contact angles of seven concentrations of imidacloprid on the surface of rice leaves in relation to the environmental relative humidity. As can be seen from the figure, the trends of the contact angles of the seven pesticide concentration solutions with increasing relative humidity were consistent with the results presented in Section 3.1.2. Overall, the contact angle was significantly different for different pesticide concentrations. The contact angles were divided into three categories. In the first category, the contact angles of the liquids

with a high degree of dilution (1:500, 1:1000, 1:2000, 1:3000, and 1:4000) were large, similar to the contact angle of water on the surface of rice leaves. In the second category, the contact angle of the moderately diluted solution (1:500) was slightly decreased compared to those in the first category, but the reduction degree was not as significant as that presented in Fig. 8. In the third category, the contact angles of the liquid with the lowest dilution levels (1:100 and 1:200) decreased significantly compared to the other categories, and the contact angle reached a minimum of approximately 85° under the condition of 40% relative humidity.

2. Two-factor interaction analysis of temperature and humidity

The two-factor univariate analysis of the leaf contact angle of rice plants with different combinations of ambient temperature and relative humidity was performed using SPSS. Finally, the influence of the two main factors, temperature and relative humidity, on the contact angle was determined. The results of the specific analysis are presented in Table 3. The results show that the effects of temperature ($p=0.231$) and relative humidity ($p=0.146$) on the contact angle of droplets on the surface of rice leaves were not significant (at a level of $p=0.05$). Under the interaction of temperature and relative humidity, the influence of the contact angle was not significant ($p=0.926$).

In addition, a response surface analysis of rice leaf contact angles under different temperature and relative humidity combinations was performed using Design-Expert software. Surface response maps and contour maps of the temperature and relative humidity are shown in Fig. 9.

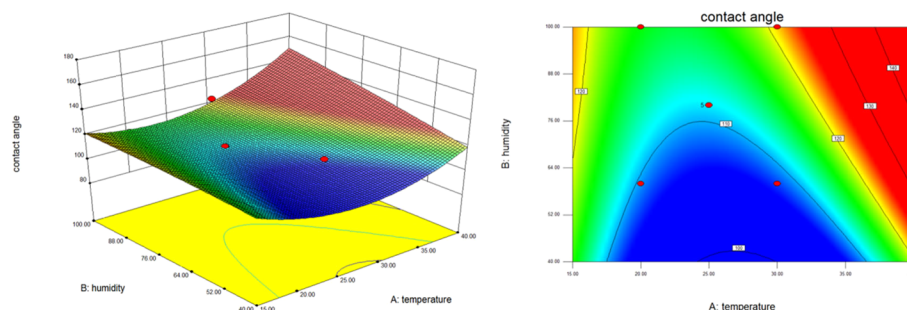


Fig. 9. Temperature and humidity versus contact angle.

Table 4. Orthogonal experimental results

Number	Temperature	Relative humidity	Pesticide formulation	Pesticide concentration	Contact angle
1	25°C	60%	WP	1:200	92.850±1.941
2	40°C	40%	SL	1:200	85.526±1.004
3	35°C	40%	WG	1:500	122.830±1.894
4	20°C	60%	SC	1:500	114.090±1.222
5	30°C	40%	WP	1:1000	118.339±1.073
6	25°C	80%	WG	1:1000	128.799±1.458
7	35°C	60%	SL	1:100	77.373±0.968
8	40°C	60%	EC	1:1000	127.889±1.129
9	40°C	100%	WP	1:500	115.055±0.731
10	35°C	100%	SC	1:1000	121.440±2.743
11	30°C	100%	EC	1:100	109.986±1.352
12	25°C	100%	SL	1:100	79.625±0.730
13	25°C	40%	SC	1:100	106.339±1.055
14	35°C	80%	EC	1:200	118.220±0.664
15	20°C	80%	WP	1:100	86.968±2.049
16	20°C	40%	EC	1:100	112.953±1.582
17	30°C	60%	WG	1:100	107.017±1.328
18	40°C	40%	WG	1:100	104.194±1.240
19	20°C	100%	WG	1:200	113.047±2.575
20	30°C	40%	SC	1:200	109.760±1.314
21	25°C	40%	EC	1:500	123.379±1.261
22	35°C	40%	WP	1:100	82.381±0.610
23	40°C	80%	SC	1:100	104.089±1.495
24	20°C	40%	SL	1:1000	119.042±1.952
25	30°C	80%	SL	1:500	108.678±1.316

As shown in Fig. 9, as the relative humidity gradually decreased from 100%, the contact angle tended to gradually decrease. As the temperature changed from 15 to 40°C, the contact angle decreased. At 25°C and 40% relative humidity, the minimum contact angle was reached (approximately 113.5°). The trend of the contact angle increased after reaching this minimum value. In addition, as the surface steadily changed, the values of the contour line and the color changed smoothly and gradually. The temperature and relative humidity had little effect on the contact angle. However, compared to temperature, humidity had a greater impact on the contact angle of droplets on the rice leaf surface.

Under the interaction of temperature and relative humidity, the change in the leaf contact angle of rice plants was also relatively stable. Therefore, it can be concluded that environmental temperature and relative humidity have no significant interactive effect on the contact angle of droplets on the surface of rice leaves.

3. Orthogonal experimental analysis

The experimental results of the 25 sets of the contact angle mixed orthogonal experimental data are presented in Table 4. The multifactor univariate analysis of the general linear model was carried out using SPSS, and the inter-subject effect test re-

sults are shown in Table 5. It can be seen from Table 5 that the effects of pesticide formulation and pesticide concentration were both significant ($p < 0.05$), indicating that they each had a significant influence on the contact angle of droplets on the surface of rice leaves. However, the F-value of the pesticide concentration factor was 29.756, and that of the pesticide formulation factor was 17.705. Therefore, the pesticide concentration had a greater influence on the contact angle than did the pesticide formulation. In contrast, the effects of ambient temperature and relative humidity were insignificant ($p > 0.05$). As discussed in Sections 3.1.1 and 3.1.2, temperature and humidity had an insignificant influence on the contact angle of droplets on the surface of rice leaves. However, humidity ($p = 0.433$) had a greater influence on the contact angle than did ambient temperature ($p = 0.461$).

The above four factors had a descending order of influence on the contact angle of droplets on the surface of rice leaves: pesticide concentration > pesticide formulation > relative humidity > temperature. When the other parameters were consistent and the dilution ratio of the pesticide concentration was 1,000 times or higher, the contact angle of droplets on the surface of rice leaves was more than 120°, and the rice leaves were hydrophobic. When the dilution ratio of the pesticide concentration was 100 times, the contact angle was approximately 85°, and the reduction rate was 29.2%.

Table 5. Tests of Between-Subjects Effects

Source	Type III Sum of Squares	df	Mean Square	F	p-value
Corrected Model	5235.184 ^{a)}	14	373.942	11.928	0.000
Intercept	254739.223	1	254739.223	8125.685	0.000
Temperature	122.702	4	30.676	0.978	0.461
Humidity	93.784	3	31.261	0.997	0.433
Pesticide formulation	2220.157	4	555.039	17.705	0.000
Pesticide concentration	2798.541	3	932.847	29.756	0.000
Error	313.499	10	31.350		
Total	294965.009	25			
Corrected Total	5548.683	24			

^{a)} R-Squared=0.944 (Adjusted R-Squared=0.864)

In addition, 29 experimental groups were designed using Design-Expert software. The interference effects of the four external factors (ambient temperature, relative humidity, pesticide formulation, and pesticide concentration) on the contact angle of droplets on the rice leaf surface were analyzed. In Fig. 10, as the design factor increased from -1 to 1 , there was a larger variation in the curve and a greater influence of the influencing factor on the contact angle of the droplet on the rice leaf surface.

The overall change in the amplitude of ambient temperature (impact factor A) was the smallest, while that of pesticide concentration (impact factor C) was the largest, and the relative humidity and pesticide formulation were in the middle (Fig. 10). Therefore, ambient temperature had the least influence on the contact angle of droplets on the rice leaf surface, while pesticide concentration had the largest influence. The degree of influence on the contact angle was pesticide concentration > pesticide formulation > relative humidity > temperature, which was consistent with the orthogonal experimental results obtained through SPSS.

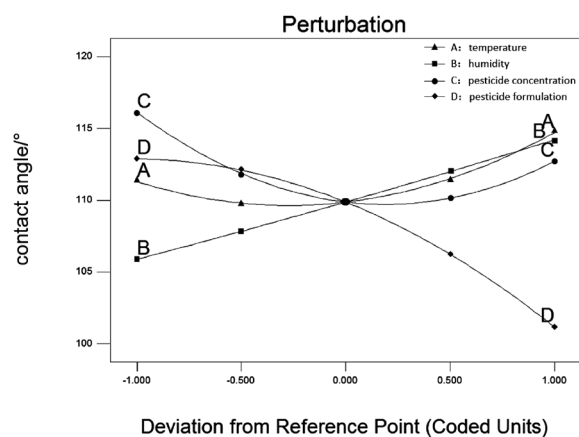


Fig. 10. Interference diagram of (A) temperature, (B) humidity, (C) pesticide concentration, and (D) pesticide formulation. NOTE: The horizontal axis of the interference graph represents the design factor of the experimental group, and the level ranges from the minimum (-1) on the left to the maximum (1) on the right, indicating that the impacts of the four external influence factors increased from small to large.

Discussion

The above experimental results show that the temperature and relative humidity of the ambient air have an effect on the contact angle of the droplets on the surface of rice leaves during plant growth. Koch *et al.*²⁹⁾ investigated the effects of relative humidity on the physical and chemical composition of leaf surface wax, morphology, and wettability of cabbage, eucalyptus, and nasturtium. The contact angles of droplets on the leaf surfaces of these three species of hydrophobic plants were measured, and gas chromatography was used to estimate the amount of wax on the leaf surfaces. The experimental results showed that high relative humidity (98%) resulted in a significantly higher amount of water contained in the leaves of cabbage, eucalyptus, and nasturtium compared to that under lower relative humidity (20–30%). The contact angle of the corresponding droplets on the blade surface was also small. In addition, the decrease in relative humidity in the air caused an increase in the amount of wax deposited on the leaf surfaces of the three plants. Therefore, the relative humidity of the air is positively correlated with the increase in wax crystal density on the surface of plant leaves and a decrease in leaf surface wettability. This is inconsistent with the change in the contact angle of droplets on the surface of rice leaves with increasing relative humidity in the air. This may be due to the uneven microstructure of the surface of the rice leaf, as it has striped grooves, stomata, many fine hairs, and a high degree of roughness.³⁷⁾

Chhasatia *et al.*³⁸⁾ studied the influence of relative humidity on the contact angle and particle deposition morphology of evaporating colloidal droplets. A high-resolution goniometer was used to measure the contact angle of droplets on a glass substrate by changing the relative humidity in the air while controlling the relevant variables. The results showed that with the increase in relative humidity, the contact angle of the droplets on the glass substrate gradually increased, which was consistent with the contact angle rule obtained by Koch *et al.*³⁰⁾ In addition, Chhasatia *et al.*³⁸⁾ used fluorescence microscopy to study the deposition behavior of inkjet-printed aqueous colloidal droplets on a glass substrate. The relative humidity in the air also affected the extent to which the droplets spread after hitting the

glass substrate. The evaporation rate at the surface of the falling glass substrate and the evaporation-driven flow conditions inside the droplets drove the suspended particles toward the contact line between the droplets and the solid surface. Chhasatia *et al.*³⁸⁾ concluded that the droplet particle deposition area and the droplet contact angle changed significantly with the relative humidity of the air. Higher deposition diameters can be observed at higher relative humidity and lower evaporation rates. This can be attributed to the lower contact angle during diffusion.

Leelamanie *et al.*³⁹⁾ found that with a decreasing relative humidity (94 to 33%) and an equivalent stearic acid content, the surface free energy of sand sample surfaces gradually increased, while the contact angle of the water droplet on the sand sample surface gradually decreased. Thus, these results on the influence of relative humidity on the contact angle of droplets on a hydrophobic fine sand surface are consistent with the results of the present study on the relationship between environmental relative humidity and the wettability of the rice leaf surface (as discussed in Section 3.1.2).

Based on the results of the above three studies, it can be concluded that the contact angle of droplets on the surfaces of materials that are hydrophobic varies with the relative humidity of the ambient air, but there is a considerable difference depending on the type of material. The reasons for this large contrast may be the result of differences in the structure of the composite materials and the surface of plant leaves. Therefore, this study has determined that the contact angle of droplets on the surface of rice leaves changes with the relative humidity of the air.

Conclusions

To improve the effect of pesticide spraying in agricultural rice fields and to reduce the necessary amount of pesticide, four external environmental factors that affect the wettability of liquid droplets in contact with the surface of rice leaves were studied. The following conclusions were drawn:

(1) The ambient temperature and relative humidity influence the contact angle of droplets on the surface of rice leaves. In the natural environment of rice growth in southern China, the contact angle did not change with a single trend of a rise in ambient temperature. With an increase in ambient temperature from 15 to 25°C, the contact angle decreased, and the effect of the droplets was gradually enhanced. With an increase from 25 to 45°C, the contact angle of the droplets on the surface of the rice leaves increased. Therefore, at an ambient temperature of approximately 25°C, the contact angle was minimized, and the wet spreading effect was optimal. In contrast, the contact angle of droplets on the surface of rice leaves changed with a single trend of an increase in environmental relative humidity. With an increase in relative humidity from 40 to 100%, the contact angle increased. Therefore, when the relative humidity of the environment was 40%, the contact angle was the smallest, and the wet spreading effect was optimal.

(2) The formulation and concentration of the pesticide solution had a significant influence on the contact angle of drop-

lets on the surface of rice leaves. Different formulations of the same pesticide had a significant influence on the contact angle. The five widely used pesticide formulations that were used in this study resulted in the following ranking of contact angles: WG>EC>SC>WP>SL. WP and SL had smaller contact angles than did the other pesticide formulations, and they therefore exhibited the best wet spreading effects. In addition, when using the same pesticide suspension formulation, the contact angles of different concentrations of the pesticide solution also exhibited significant differences. With increasing pesticide concentration, the contact angle gradually increased, and the wetting and spreading effects gradually decreased. Therefore, the use of high-concentration (1:100 or 1:200) WP or SL formulations during spraying operations can improve the spreading effect of the liquid on the surface of rice leaves.

(3) By designing 25 sets of contact angle orthogonal experiments, the degrees of influence of the four external factors were ranked from large to small as pesticide concentration, pesticide formulation, relative humidity, and temperature. The most important external environmental factors affecting the wetting properties of droplets on rice leaves were pesticide formulation and pesticide concentration. According to the results of the hybrid orthogonal test and the single factor test, when the concentration of sprayed pesticide was increased and the pesticide formulation was WP or SL, the contact angle was greatly reduced. When the droplets are in contact with the surface of rice leaves, the wetting and spreading effects are greatly enhanced, and the rice leaves can be converted from hydrophobic to hydrophilic.

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Conflicts of interest

The authors declare no conflicts of interest.

Author contribution statement

Conceptualization, J.Z. and T.Z.; funding acquisition, J.Z. and S.W.; software, J.Z. and S.W.; writing—original draft preparation, T.Z., J.Z., and S.W.

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